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Evidence for Decays of h_c to Multi-Pion Final States

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Abstract

Using a sample of 2.59×10^7 $\psi(2S)$ decays collected by the CLEO–c detector, we present results of a search for the decay chain $\psi(2S) \to \pi^0 h_c, h_c \to n(\pi^+\pi^-)\pi^0, n = 1, 2, 3$. We observe no significant signals for $n = 1$ and $n = 3$ and set upper limits for the corresponding decay rates. First evidence for the decay $h_c \to \pi^+\pi^-\pi^+\pi^-\pi^0$ is presented, and a product branching fraction of $B(\psi(2S) \to h_c) \times B(h_c \to 2(\pi^+\pi^-)\pi^0) = 1.88^{+0.48+0.47}_{-0.45-0.30} \times 10^{-5}$ is measured. This result implies that $h_c \to$ hadrons and $h_c \to \gamma\eta_c$ have comparable rates, in agreement with expectations.

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Although the field of charmonium spectroscopy is now thirty-five years old, data on the $c\bar{c}$ singlet state, the $h_c(^1P_J)$, remains sparse. Two experiments have identified the h_c and accurately measured its mass. The CLEO [1, 2] measurements were made using the decay chain $\psi(2S) \to \pi^0 h_c, \pi^0 \to \gamma\gamma, h_c \to \gamma\eta_c$, and identifying the h_c either by fully reconstructing the event using many different hadronic decay channels of the η_c, or by reconstructing the π^0 and γ in the decay chain and inferring the existence of the η_c. The E835 experiment [3] made scans of antiproton energy and observed the reaction $\bar{p}p \to h_c \to \gamma\eta_c, \eta_c \to \gamma\gamma$. The experiment also searched for the evidence of the h_c in the previously reported isospin-suppressed decay $h_c \to \pi^0 J/\psi$ but none was found. The h_c is also expected to decay directly to multi-hadron final states; however, such decays have yet to be observed. The h_c width into such states is expected to be, by coincidence, comparable to that of the radiative decays; Godfrey and Rosner [4] predict branching fractions of 38% for $\gamma\eta_c$ decays and 57% ggg decays, with the remainder being γgg. The h_c, unlike the χ_{cJ} mesons, has negative G-parity, and thus its multi-pion decays are likely to involve an odd number of pions. Here we report the results of a search for the decays of the h_c into $n(\pi^+\pi^-)\pi^0$, with $n = 1, 2, 3$.

The data presented here were taken by the CLEO-c detector [5] operating at the Cornell Electron Storage Ring (CESR) with e^+e^- collisions at a center of mass energy corresponding to the $\psi(2S)$ mass of 3.686 GeV. The data correspond to an integrated luminosity of 56.3 pb^{-1} and the total number of $\psi(2S)$ events, determined according to the method described in [6], is calculated as $(2.59 \pm 0.05) \times 10^7$. Like the previous CLEO analyses, we search for the h_c mesons produced by the isospin-violating decay $\psi(2S) \to \pi^0 h_c$.

Charged particles are detected in a cylindrical wire chamber system immersed in a 1.0 T axial magnetic field induced by a superconducting solenoid. The solid angle for detecting charged particles is 93% of 4π, and the resolution 0.6% at 1 GeV. To identify the pions, we measure the specific ionization, dE/dx, in the drift chamber and require that it be within 4 standard deviations of that expected for a pion. Photons are detected using the CsI crystal calorimeter also inside the magnet coil, which has an energy resolution of 2.2% at 1 GeV and 5% at 100 MeV. Photon candidates are required to have a lateral shower shape consistent with that expected for a photon and not to align with the projection of any charged particle into the calorimeter. We combine photon pairs to make π^0 candidates, and kinematically constrain them to the known π^0 mass; combinations with a χ^2 of less than 10 for the one degree of freedom are retained for further analysis.

For each decay mode, we combine the requisite number of charged pion candidates with one π^0 candidate to form an h_c candidate. These particles are kinematically constrained with the beamspot to form a primary event vertex. We then add a second π^0 candidate in the event, ensuring that no photon is used in both candidates, to make a $\psi(2S)$ candidate. This $\psi(2S)$ candidate is then kinematically constrained to the four-momentum of the beam, the energy of which is calculated using the known $\psi(2S)$ mass. The momentum is non-zero only due to the crossing angle (≈ 3 mrad per beam) in CESR. To make our final selection, we require the $\psi(2S)$ candidate to have a χ^2 of less than 25 for the four degrees of freedom for this fit; this requirement rejects most background combinations.

The kinematic fit produces an h_c mass resolution which is much improved over a direct measurement of $M(n(\pi^+\pi^-)\pi^0)$ and slightly improved compared to a measurement of the missing mass using the measured parameters of the transition π^0 alone. To study the efficiency and resolutions, we generated Monte Carlo samples for each h_c decay using a GEANT-based detector simulation [8]. The decay products of the h_c were generated according to phase space. For each of the three muliti-pion decays sought, the MC studies

show that the h_c mass distribution is well-represented by a double Gaussian signal shape over a slowly varying background. For the $n = 2$ case, for example, the shape parameters are $\sigma_{narrow} = 1.19$ MeV, $\sigma_{wide} = 3.18$ MeV, and $N_{narrow}/N_{total} = 0.643$. The efficiencies are shown in Table I.

TABLE I: For each h_c decay mode, the efficiency, the raw event yield with statistical uncertainties obtained from the fit to the data, and the product branching fraction $B_1 \times B_2$, where $B_1 = B(\psi(2S) \to \pi^0 h_c)$, and $B_2 = B(h_c \to n(\pi^+\pi^-)\pi^0)$, including systematic uncertainties. Upper limits are quoted at 90% confidence level, and include the effects of systematic errors as described in the text.

Mode	efficiency (%)	Yield	$B_1 \times B_2 \times 10^5$
$\pi^+\pi^-\pi^0$	27.0	$1.6^{+6.7}_{-5.9}$	< 0.19
$2(\pi^+\pi^-)\pi^0$	18.8	92^{+23}_{-22}	$(1.88^{+0.48+0.47}_{-0.45-0.30})$
$3(\pi^+\pi^-)\pi^0$	11.5	35 ± 26	$(1.2 \pm 0.9 \pm 0.3)$ (< 2.5)

The final invariant mass distributions are shown in Figs. 1(a), 2(a) and 1(c). In the case of $h_c \to \pi^+\pi^-\pi^0$ the events are dominated by $\psi(2S) \to \pi^0\pi^0 J/\psi$, with the subsequent decay of the J/ψ into two charged particles. The J/ψ has a very large branching into $\mu^+\mu^-$ and these events will, in general, pass all selection criteria and enter the plot (Fig. 1(a)). The most efficacious way of eliminating these events is to reject those events with $3.0 < M_{\pi^+\pi^-} < 3.2$ GeV/c^2. Figure 1(b) shows the plot after this cut has been made. Neither Figs. 1(a) or 1(b) show any excess in the h_c region. These histograms are fit to a background function (second order polynomial for Fig. 1(a) and an ARGUS style background function [9] for Fig. 1(b)), and signal function of fixed mass and width; the h_c mass is taken from [2] to find 90% confidence level upper limits of < 94 and < 14 events respectively.

Fig. 2(a) shows the invariant mass distribution for $h_c \to 2(\pi^+\pi^-)\pi^0$. It shows a distinct excess in the region of the h_c. The distribution is fit to an ARGUS style background function, plus a floating mass signal with a fixed shape from the Monte Carlo studies. The measured peak mass is 3525.6 ± 0.5 MeV, which may be compared with the Particle Data Group [7] number of 3525.93 ± 0.27 MeV and the more recent CLEO [2] measurement of 3525.28 ± 0.22 MeV. The yield is 92^{+23}_{-22} events, and has a significance of 4.4σ. We also analyzed a large sample of Monte Carlo events generated using the known decays of the $\psi(2S)$ and designed to mimic the real data sample. Those events where an h_c meson was generated are explicitly excluded. Figure 2(b) shows the $2(\pi^+\pi^-)\pi^0$ mass plot from the remaining events and, as expected, it shows no sign of an excess in the h_c region. This mass distribution falls slightly faster than the equivalent one in data, demonstrating the lack of complete knowledge of $\psi(2S)$ decays, but it can be well fit by an ARGUS type background function.

Fig. 1(c) shows the mass distribution for $h_c \to 3(\pi^+\pi^-)\pi^0$. It shows a small, but not statistically signficant, excess in the signal region. The fit shown uses the same fixed mass of the h_c and the measured yield is 35 ± 26 events, corresponding to a 90% confidence level upper limit of 70.

We consider systematic uncertainties from many different sources, and these are listed for the $2(\pi^+\pi^-)\pi^0$ mode in Table II. We assign uncertainties of 0.3% and 2%, respectively, on the detection efficiency for each track and for each photon. The largest systematic uncertainty in the $2(\pi^+\pi^-)\pi^0$ mode is due to uncertainties in the fitting procedure. The fit is performed in small mass bins to minimize fluctuations due to choice of binning, and has a χ^2 per degree freedom of 242/235. Using a background function of a second order

Chebyshev polyomial gives higher yields but a less satisfactory fit. Fits are also performed over wider and narrower mass ranges and using higher order polynomial background shapes. The systematic uncertainty is calculated from observing the range of yields from different, reasonable, fitting procudures. The h_c is known to be relatively narrow and our Monte Carlo simulation assumed an intrinsic width of 0.9 MeV. We assign a systematic uncertainty based upon the variation of yield if this number was in the range 0-1.5 MeV. To evaluate the systematic uncertainty due to our knowledge of the resolution, we allowed for variations of up to 10% in the width of the resolution function. To account for possible substructure in the 5π decay products a series of Monte Carlo samples were generated where the π mesons are the product of intermediate ρ mesons, and we look at the spread of different efficiencies calculated.

To convert the yields to product branching fractions, we divide by the product of the number of $\psi(2S)$ events in the data sample and the efficiency from Table I. For evaluating the limits in the cases where there is no significant signal, we take the probability density function and convolve this with Gaussian systematic uncertainties. We then find the branching fraction that includes 90% of the total area.

TABLE II: Systematic uncertainties for the $2(\pi^+\pi^-)\pi^0$ mode.

Source	Uncertainty (%)
Efficiency of tracks and photons	10%
Background function and fitting range	$^{+25}_{-4}\%$
χ^2 cut efficiency	4%
Signal natural width	5%
Signal resolution	8%
Possible substructure	6%
Possible decays to J/ψ	$^{+0}_{-3}\%$
$N(\psi(2S))$	2%
Total	$^{+29}_{-16}\%$

The product branching fraction, $B(\psi(2S) \to h_c) \times B(h_c \to 2(\pi^+\pi^-)\pi^0)$ is calculated to be $(1.88^{+0.48+0.47}_{-0.45-0.30}) \times 10^{-5}$. We note that this is $\approx 5\%$ of $B(\psi(2S) \to h_c) \times B(h_c \to \gamma\eta_c)$ [2]. Given the large number of different hadronic final states that are available for h_c decays, we can conclude that these hadronic states have a width the same order of magnitude as the radiative decays into the η_c.

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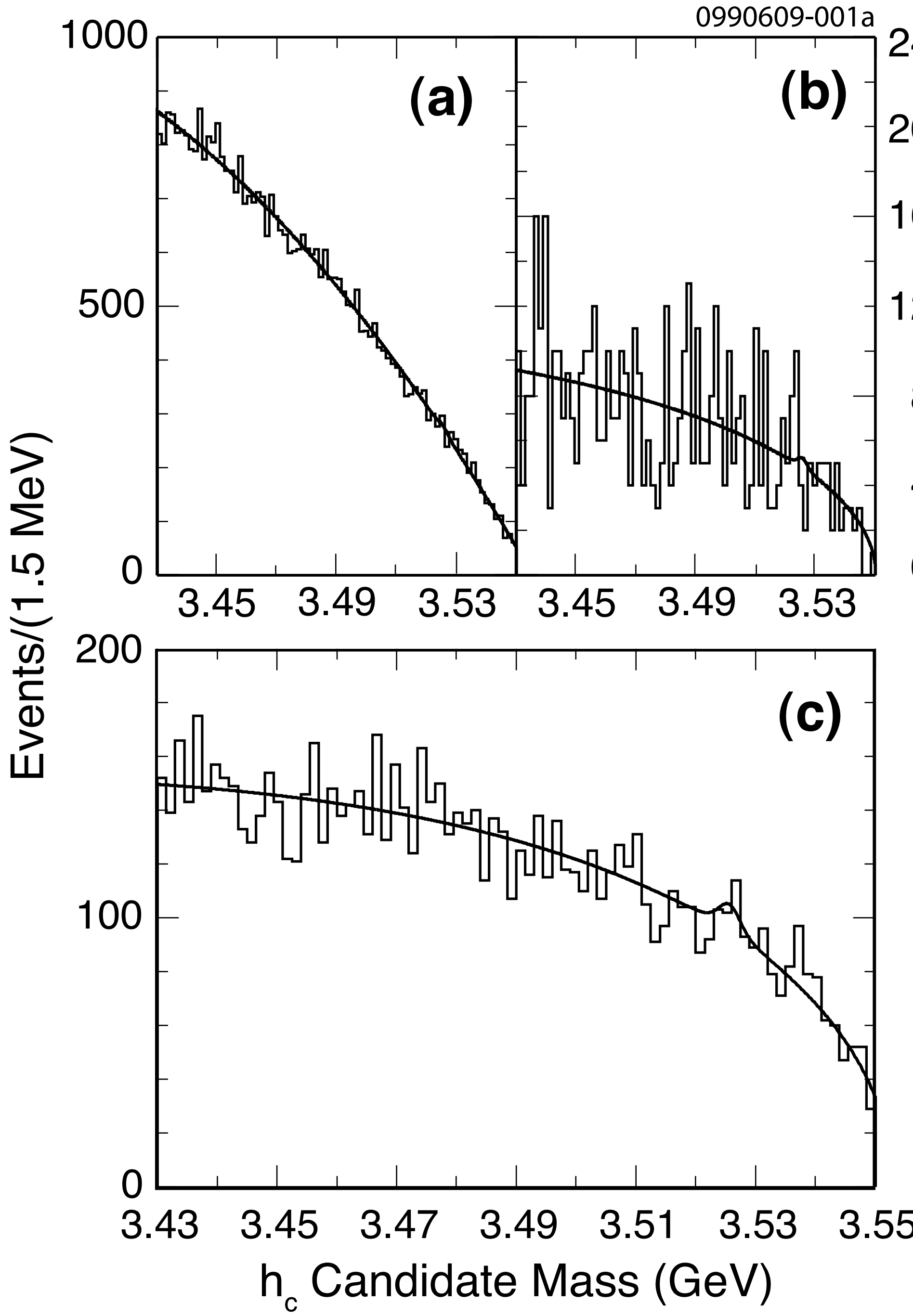

FIG. 1: Invariant mass plots for (a) $\pi^+\pi^-\pi^0$ (b) $\pi^+\pi^-\pi^0$ with a J/ψ veto (c) $3(\pi^+\pi^-)\pi^0$. Fig 1(a) is fit using a second order Chebychev polynomial shape background. Figs. 1(b), and 1(c) are fit using an ARGUS type background function.

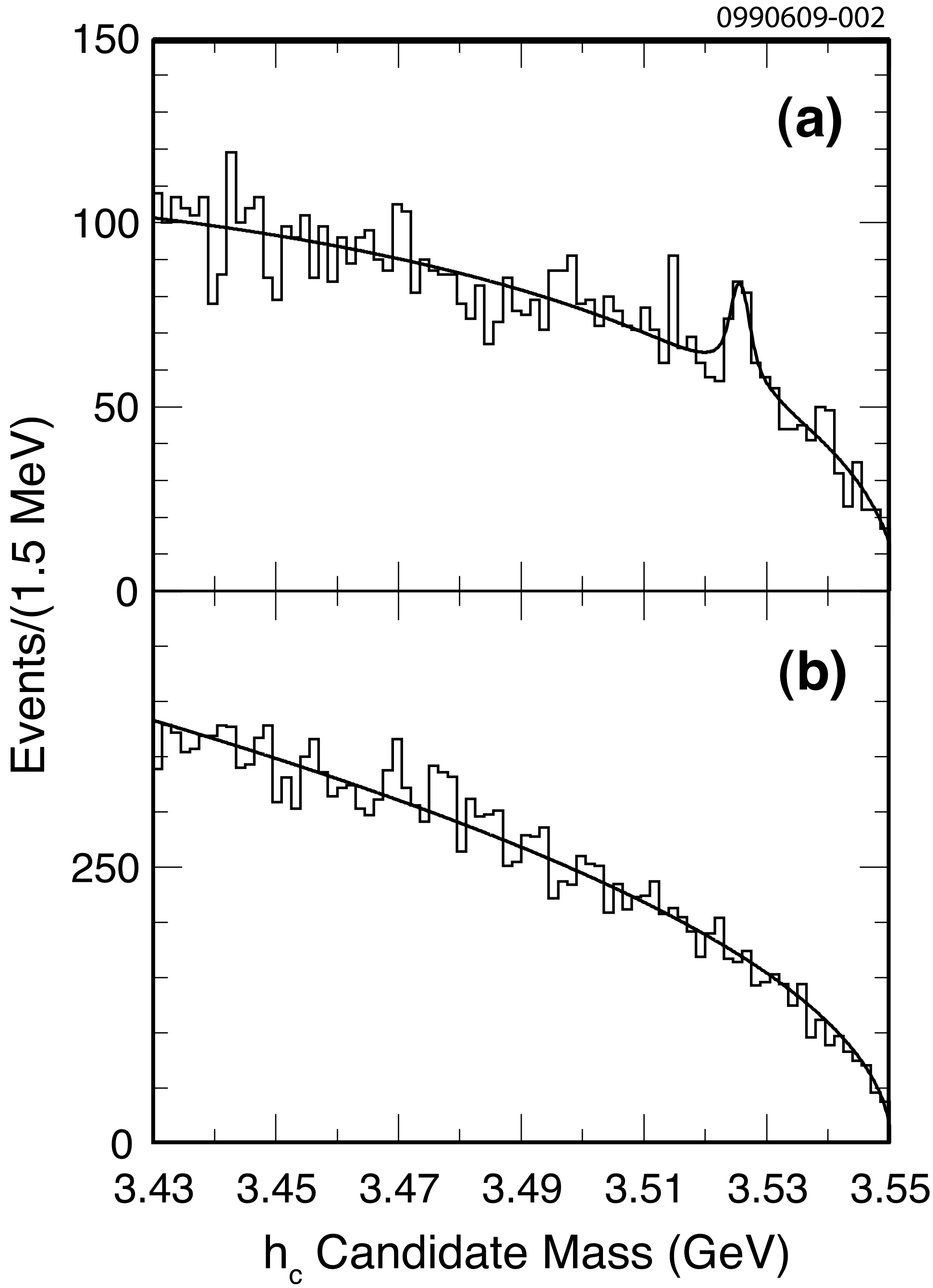

FIG. 2: Invariant mass plots for $2(\pi^+\pi^-)\pi^0$ for (a) data, and (b) non-h_c Monte Carlo events. In each case the background function is an ARGUS type function.

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